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Role of syllable segmentation processes in peripheral word recognition

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ABSTRACT

Previous studies of foveal visual word recognition provide evidence for a low-level syllable decomposition mechanism occurring during the recognition of a word. We investigated if such a decomposition mechanism also exists in peripheral word recognition. Single words were visually presented to subjects in the peripheral field using a 6° square gaze-contingent simulated central scotoma. In the first experiment, words were either unicolor or had their adjacent syllables segmented with two different colors (color/syllable congruent condition). Reaction times for correct word identification were measured for the two different conditions and for two different print sizes. Results show a significant decrease in reaction time for the color/syllable congruent condition compared with the unicolor condition. A second experiment suggests that this effect is specific to syllable decomposition and results from strategic, presumably involving attentional factors, rather than stimulus-driven control.

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1. Introduction

Patients with central field loss usually exhibit poor reading performance compared to normally-sighted readers (Elliott et al., 1997). Difficulties in identifying letters and words are linked to the perceptual and oculo-motor limitations caused by the constrained use of peripheral vision. Visual perceptual limitations in peripheral vision increase with spatial eccentricity and include low spatial resolution (Mandelbaum & Sloan, 1947; Wertheim, 1980; Westheimer, 1979; Weymouth, 1958), low contrast sensitivity (Pointer & Hess, 1989; Rijdsdijk, Kroon, & van der Wildt, 1980; Rubin & Legge, 1989), positional uncertainty (Chung & Legge, 2009; Levi, Klein, & Yap, 1987) and crowding (Levi, 2008). Presenting text in a high-contrast format with a large print size reduces most of these peripheral limitations but does not allow patients to reach the reading performance of normally-sighted subjects (Chung, Mansfield, & Legge, 1998). This is because crowding is not completely removed by using a large print size (Pelli et al., 2007), and because the duration of visual processing in periphery is higher compared to central vision (Cheong et al., 2008). Moreover, patients with central field loss have difficulties in controlling their eye movements (Rubin & Feely, 2009; Seiple et al., 2005) and

in positioning a word on a healthy part of the retina such as their Preferred Retinal Locus (Schuchard & Fletcher, 1994; Timberlake et al., 1986) or the locus where word recognition performance would be optimal (Yao-N'dré, Castet, & Vitu, 2013). These perceptual and oculo-motor limitations are both suggested to cause the high number of fixations needed by patients with central field loss to read a text (Legge et al., 1997).

Written word recognition is a complex process based on different steps involving bottom-up and top-down mechanisms (McClelland & Rumelhart, 1981; see Balota, Yap, & Cortese, 2006 for a review). Pelli, Farell, and Moore (2003) showed that the word recognition process cannot bypass a primary step based on letter recognition following the detection of letter features (Pelli et al., 2006). Psycholinguistic studies also showed the existence of intermediary steps between letter and word recognition: Early level perceptual operations in word recognition involve sublexical units, such as morphemes or syllables, in order to access the words' lexicon (Balota, Yap, & Cortese, 2006; Grainger, 2008). The functional role of the syllable has been extensively studied in different languages (Ans, Carbonnel, & Valdois, 1998; Carreiras, Vergara, & Barber, 2005; Conrad, Grainger, & Jacobs, 2007; Ferrand, 2000; Ferrand & New, 2003; Prinzmetal, Treiman, & Rho, 1986; Spoehr & Smith, 1973). Prinzmetal, Treiman, and Rho (1986) suggested that syllables form perceptual groups within words based on evidence that subjects are more likely to judge a letter's color to be similar to the color of letters within its syllable than to the color of letters in an adjacent syllable. More recently, studies in English,

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French, German, and Spanish languages showed an inhibitory effect of syllable frequency on word recognition in both lexical decision and naming tasks (Carreiras, Alvarez, & Devesa, 1993; Conrad & Jacobs, 2004; Macizo & Van Petten, 2007; Mathey & Zagar, 2002). These studies found a negative effect of syllable frequency on word lexical decision and naming latencies, suggesting an early pre-lexical activation of syllabic units and corresponding words. Effect of the number of syllables within a word has also been shown in visual word recognition and naming in French (Ferrand & New, 2003). Finally, Carreiras, Vergara, and Barber (2005) showed that visual segmentation of syllables in Spanish language (adjacent syllables have different colors) during a lexical decision task affects early ERP components involved in word recognition, suggesting that syllables could be sublexical representations dissociable from lexical representations involved in the process of word recognition.

In this study, our main goal was to test if a similar syllable decomposition process occurs in periphery where word recognition is slowed down by perceptual and oculo-motor factors. To do so, we used two different colors to segment the different syllables within a word. This condition was referred to as the color/syllable congruent condition. As a reference condition, we used unicolor words in which all letters were black. In Experiment 1, our rationale was the following: if a syllable decomposition mechanism is at work in the periphery, color-induced segmentation of syllables should improve word identification performance compared to the unicolor condition. To anticipate the results, we did find that performance was higher in the color/syllable congruent condition than in the unicolor condition. In the second experiment, our aim was twofold: We first wanted to control whether the effect observed in Experiment 1 implied a specific syllable decomposition mechanism rather than a more general mechanism that simply improves location encoding or reduces crowding for some letters (those located at the color boundaries). This was achieved by adding a third condition where two different colors were used to segment a word, but without preserving the congruence between colors and syllables (the color/syllable incongruent condition). The second aim of Experiment 2 was to investigate whether the effect observed in Experiment 1 was under stimulus-driven control (i.e. the observer gets a low-level automatic response to the visual input), rather than strategic control (i.e. the observer uses deliberate cognitive strategies to decode the visual input (Sperling and Doshier, 1986, chap. 2; Strayer & Kramer, 1994)). This was tested by randomly mixing trials from the three different conditions within a block (see Table 1 for the differences in the experimental designs of Experiments 1 and 2). There were two predictions in Experiment 2. First, if the effect observed in Experiment 1 was due to some letter localization improvements induced by color boundaries without any role of syllable decomposition, then both bicolor conditions should improve performance compared to the unicolor condition. Second, if the effect observed in Experiment 1 (unicolor vs. color/syllable congruence) was under strategic control, its amplitude should be reduced or abolished in Experiment 2, whose mixed design prevents the use of any strategic component.

Table 1
Experimental designs of Experiments 1 and 2.

Condition	Experiment 1 (blocked design)	Experiment 2 (mixed design)
Unicolor	Yes	
Color/syllable congruence	Yes	Yes
Color/syllable incongruence	No	

2. Methods

2.1. Subjects

Sixteen young subjects with normal or corrected-to-normal vision and aged from 22 to 26 participated in this study. Informed consent was obtained from each observer after the nature and purpose of the experiment had been explained. The work was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). Ten subjects participated in Experiment 1 and six new (did not participate in Experiment 1) participated in Experiment 2. Each subject was able to discriminate the black and the red colors that were used in our experiments.

2.2. Apparatus

Stimuli were displayed on a 21-in. CRT color monitor (GDM-F520, Sony, Japan, refresh rate = 100 Hz, resolution = 1152×854 pixels) driven by a PC computer running custom software developed in C and using graphic libraries. Subjects sat in a reclining chair with their eyes at a distance of 40 cm from the monitor in a dimly lit room. They viewed the screen with their dominant eye while wearing a patch over the contralateral eye.

2.3. Artificial scotoma

Our purpose was to simulate the vision of patients with central field loss (for instance patients with Age-Related Macular Degeneration) who can only use their peripheral vision. An eye-tracker was used to simulate an artificial scotoma (i.e. an area centered on the macula where subjects cannot extract any visual information) based on a gaze-contingent system: the subject's gaze position was used in real-time to remove from the computer screen the visual information corresponding to the macular position. A six-degree square central scotoma was simulated for each of our subjects with an Eyelink II head-mounted eye tracker (SR Research Ltd., Mississauga, Ont., Canada) by using the same procedure as in our previous work (Bernard, Scherlen, & Castet, 2007; Scherlen et al., 2008). The pupil of the dominant eye was tracked at a frequency of 500 Hz and used to display the gaze-centered scotoma with a delay less than 12 ms (Bernard, Scherlen, & Castet, 2007). A 9-point gaze calibration followed by a 9-point gaze validation was performed before each experimental block. Each trial was triggered by the observer who pressed a button while he/she was fixating a central dot. This was used to perform an offset correction (called "drift correction" in the Eyelink terminology) at the beginning of each trial. This offset correction value was also saved and used in our data analysis to remove trials followed by an offset correction larger than 1° . The scotoma had the same texture as the background (a white background set to maximum available luminance, 100 cd/m^2). For more detailed information concerning our paradigm, see Bernard, Scherlen, and Castet (2007).

2.4. Words and syllables

A set of 1200 French words was used in Experiment 1. This set was composed of 600 low-frequency words (range: 4.3–6 occurrences per million) and 600 high-frequency words (range: 24.7–200 occurrences per million). Each frequency group contained 300 words composed of two "orthographic syllables" and 300 words composed of three "orthographic syllables". The lexical frequency of the words, the number and the locations of the French orthographic syllables were taken from the French corpus Lexique2 (New et al., 2004), a corpus that contains a set of 135,000 French words and their orthographic and phonologic characteristics. The

Condition	2 syllables	3 syllables
Unicolor	bonjour	carafe
Color/syllable congruence	bonjour	carafe
Color/syllable incongruence	bonjour bonjour	carafe carafe carafe

Fig. 1. Examples of 2 and 3-syllable words. The unicolor and the color/syllable congruent conditions were run in Experiment 1 (blocked design). The unicolor, the color/syllable congruent and the color/syllable incongruent condition were run in Experiment 2 (mixed design).

definition of orthographic syllables assumes that each vowel is pronounced in a word. For instance with this definition, the French word 'banane' is constituted by 3 orthographic syllables ('ba-nane') whereas in common oral French language, this word is constituted by 2 phonetic syllables (/ba.nan/). Words with 2 identical successive letters were not included in the experiment, given the uncertainty about the inter-syllabic boundary position: for instance, it is not clear if the orthographic segmentation for the word "barre" should be 'ba-rre', 'bar-re' or 'barr-e'. Words composed of two orthographic syllables had an average number of 5.83 ± 1.10 (SD) characters, an average frequency of 4.99 ± 0.49 occurrences per million for low frequency words and an average frequency of 58.09 ± 39.26 occurrences per million for high frequency words. Words composed of three orthographic syllables had an average number of 7.70 ± 1.24 characters, an average frequency of 5.02 ± 0.47 occurrences per million for low frequency words and an average frequency of 58 ± 36.71 occurrences per million for high frequency words. In Experiment 2, we used a set of 1200 low-frequency words. Six hundred words were composed of two orthographic syllables (average number of characters: 5.81 ± 1.27 , average frequency of 5.02 ± 1.00) and six hundred words were composed of three orthographic syllables (average number of characters: 7.84 ± 1.27 , average frequency of 5.21 ± 1.06). Each subject never saw a word more than once.

2.5. Display

The Times New Roman font was used in our experiments. We used two character print-sizes defined by the lowercase x-height: 0.5° (11 pixels on the screen) and 1° (22 pixels on the screen). The large print size (x-height = 1°) corresponds to the average Critical Print Size (i.e. the threshold size when print-size is no longer a limiting factor of reading performance, Chung, Mansfield, & Legge, 1998) for subjects using a similar scotoma in one of our previous experiments (Bernard, Scherlen, & Castet, 2007). The smaller print size (x-height = 0.5°) is close to word acuity at an eccentricity of 3° in Abdelnour and Kalloniatis (2001).

To elicit a clear segmentation between groups of letters, we used two different colors (black and red¹). Fig. 1 shows examples of words made from two and three syllables in the different color conditions. In each condition, letter stimuli were presented against a white background set to maximum available luminance (100 cd/m^2). For the unicolor condition (used in Experiments 1 and 2), letters were displayed in black (luminance: 0.3 cd/m^2). For the color/syllable congruent condition (used in Experiments 1 and 2), each consecutive syllable was displayed in a different color that

could be black (luminance: 0.3 cd/m^2) or red (luminance: 20 cd/m^2). Weber contrasts were approximately 99% for black letters and 80% for red letters.

For the color/syllable incongruent condition (used in Experiment 2), each syllabic boundary was randomly shifted by one letter to the left or to the right: Words kept the same number of colored groups, but these units were no longer the syllables of the word. In the two bicolor conditions, the first group of letters was displayed in black, and the following groups were successively displayed in red and black so that each sub-unit had a different color from its neighbors.

2.6. Procedure

Subjects with simulated central scotoma were instructed to move their eye to recognize as quickly as possible a randomly-chosen word presented at the center of the screen. Fig. 2 describes the procedure of the experiment across time: First, the observer was asked to fixate a dot centered on the screen. When the observer was ready for the trial, he/she pressed the button of a hand-held joypad. This triggered an offset correction (drift correction in the Eyelink terminology) and started the trial: a word was displayed, justified at the center of the screen (i.e. centered at the position where the observer was fixating). After making one or several saccades, the observer pressed the button of the joypad once he/she thought he/she recognized the word. This press recorded the reaction time and removed the word from the screen as the observer named it. Finally, the experimenter reported if the word had been correctly identified and gave verbal feedback to the subject in case of errors. The subject could not correct his/her response if the word was incorrectly named. For each trial, the response and the reaction time (defined as the time between the two button pressures) were saved to be used in future analysis. We ran two experiments. Ten subjects participated in Experiment 1 and six new (did not participate in Experiment 1) participated in Experiment 2. For each experiment, subjects performed three experimental sessions (1 h duration for each session) on three successive days. In Experiment 1, the unicolor and color/syllable congruent conditions were blocked: each session was an alternating succession of blocks constituted by 20 syllable-segmented colored words or 20 unicolor words (Fig. 1). Print-size was blocked with an alternative succession of lower and higher print-size blocks. Frequency was counter-balanced within each block. The number of blocks ran by each observer in one session depended on how difficult the task was for the observer (i.e. how many trials were ran during a 1 h session). For each session, subjects ran the same number of blocks for the two different color conditions and the two different print-sizes. In Experiment 2, in contrast to Experiment 1, the different experimental conditions were mixed: Trials corresponding to the unicolor, color/syllable congruent and color/syllable incongruent conditions were randomly interleaved within blocks of 20 trials. In both experiments, subjects were never informed that the different groups of letters corresponded to the orthographic syllables of each word.

2.7. Statistical analysis

Linear mixed-effect models were used to analyse reaction time data from Experiments 1 and 2 with the software R and the nlme package (Pinheiro & Bates, 2000). In these models, the dependent variable was the natural logarithm transform of the reaction times (word identification times). The random effect was the subject factor. The fixed effects used to analyse results of Experiment 1 were (1) the color-condition categorical factor (two levels: unicolor and color/syllable congruence), (2) the order of a trial to allow for learning effects, (3) the letter size (two levels: 0.5° and 1°) and

¹ For interpretation of color in Fig. 1, the reader is referred to the web version of this article.

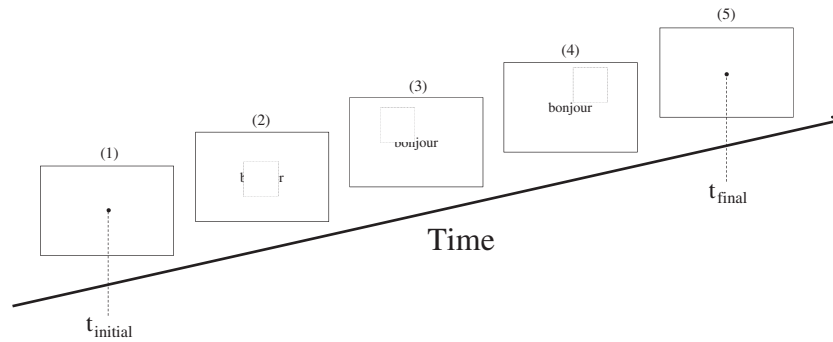


Fig. 2. Description of the procedure for Experiments 1 and 2: The subject fixates a dot with his/her fovea (1), presses a button (t_{initial}) to display the word (and the gaze-contingent central scotoma centered on the foveal fixation). (2) The subject makes one or several saccades to identify the presented word (3 and 4). Finally, the subject presses the button again (t_{final}) when he/she has recognized the word before naming the word (5). The difference $t_{\text{final}} - t_{\text{initial}}$ is defined as the reaction time.

(4) the word frequency in occurrences per millions of words. Two interactions were included: (a) between color-condition and size, and (b) between color-condition and frequency.

To analyse results of Experiment 2, we used the subject factor as the random effect. The fixed effects were: (1) the color-condition categorical factor (three levels: unicolor, color/syllable congruence and color/syllable incongruence) and (2) the rank of a trial. Character-size and frequency factors present in Experiment 1 analysis were excluded because only low frequency and smaller character-size words were used in Experiment 2. In both experiments and for (1) the color condition, (2) the rank of trials, (3) the print-size and (4) the frequency factors, the reference values were respectively defined as: (1) the unicolor color condition, (2) the average rank of trials ran by the subject, (3) the 0.5° print size and (4) the average word frequency for all the words ran by the subject. Assumptions underlying the models were visually checked with diagnostic plots of residuals. Data points with absolute standardized residuals exceeding 2.5 standard deviations were removed after a first mixed-model analysis (Baayen, Davidson, & Bates, 2008), and final results were obtained from a second analysis without these outliers.

3. Results

3.1. Recognition rate

In Experiment 1, recognition rates were high with small differences between the unicolor and color/syllable congruent conditions. For words presented in the smaller print-size, average and standard deviation values were $85 \pm 8\%$ for the low frequency words ($92 \pm 7\%$ for the high frequency words) in the unicolor condition vs. $88 \pm 5\%$ for the low frequency words ($94 \pm 3\%$ for the high frequency words) in the color/syllable congruent condition. For words presented in the larger print size, average values were $97 \pm 2\%$ for the low frequency words ($98 \pm 2\%$ for the high frequency words) in the unicolor condition vs. $98 \pm 5\%$ for the low frequency words ($99 \pm 3\%$ for the high frequency words) in the color/syllable congruent condition. In Experiment 2, recognition rates were similar to those obtained in Experiment 1 for the low frequency and smaller print-size words: They were respectively $88 \pm 5\%$, $92 \pm 6\%$ and $89 \pm 6\%$ for the unicolor, color/syllable congruent condition and color/syllable incongruent condition.

In Experiments 1 and 2, there was no significant difference in recognition rate between the unicolor and color/syllable congruent conditions for each size/frequency condition. In Experiment 1, the 95% confidence intervals for the recognition rate difference between the unicolor and color/syllable congruent conditions were $[-0.19; 0.26]$ for the low frequency/smaller size condition, $[-0.18; 0.22]$ for the

high frequency/smaller size condition, $[-0.13; 0.14]$ for the low frequency/larger print size condition, and $[-0.10; 0.12]$ for the high frequency/larger print size condition. In Experiment 2, the confidence intervals were $[-0.17; 0.25]$ for the recognition rate difference between the unicolor and color/syllable congruent conditions, $[-0.22; 0.18]$ for the recognition rate difference between the unicolor and color/syllable incongruent conditions and $[-0.24; 0.19]$ for the recognition rate difference between the color/syllable congruent and color/syllable incongruent conditions.

3.2. Reaction time

Reaction time analyses were only based on correctly identified trials.

3.2.1. Experiment 1

Experiment 1 had a *blocked* design with two color conditions: the unicolor and the color/syllable congruent condition (see Table 1). Table 2 shows the results of our linear mixed-effects model analysis for the fixed effects. The estimated value of the intercept is 8.40, equivalent to a reaction time of 4.45 s which corresponds to the average reaction time for the reference values of the fixed effects (unicolor condition, average rank of trials ran by the subject, 0.5° print size and average word frequency). There is a significant effect of the rank of trials (a 8.77% decrease in reaction time per 100 trials when other parameters corresponded to baseline values), of the character-size (74.89% decrease in reaction time for the larger print size compared to the smaller print size) and of the word frequency (13.45% decrease in reaction time when the frequency is increased by 100 occurrences per million) on reaction time. These results are not surprising, given the learning effect observed with a simulated central scotoma in normally-sighted

Table 2

Fixed effects results of the linear mixed-effects model for Experiment 1. Results show: the effect of the rank of trials (#trial), the effect of the print size (Size), the effect of the color/syllable congruent condition compared to the unicolor condition (Color), the effect of the lexical word frequency (Frequency), the interaction effect between the print size and the color condition (Size * Color) and the interaction effect between the lexical word frequency and the color condition (Frequency * Color). AIC represents the Akaike Information Criteria for the model.

	AIC: 14189.86	Estimate	Std. error	DF	t-value	p-value
(Intercept)		8.4	0.12	7800	72	$<10^{-5}$
#trial		-0.00092	0.00014	7800	-6.6	$<10^{-5}$
Size		-1.4	0.034	7800	-41	$<10^{-5}$
Color		-0.095	0.017	7800	-5.5	$<10^{-5}$
Frequency		-0.0014	0.00021	7800	-6.7	$<10^{-5}$
Size * Color		0.14	0.047	7800	2.9	0.0033
Frequency * Color		0.00053	0.00029	7800	1.9	0.063

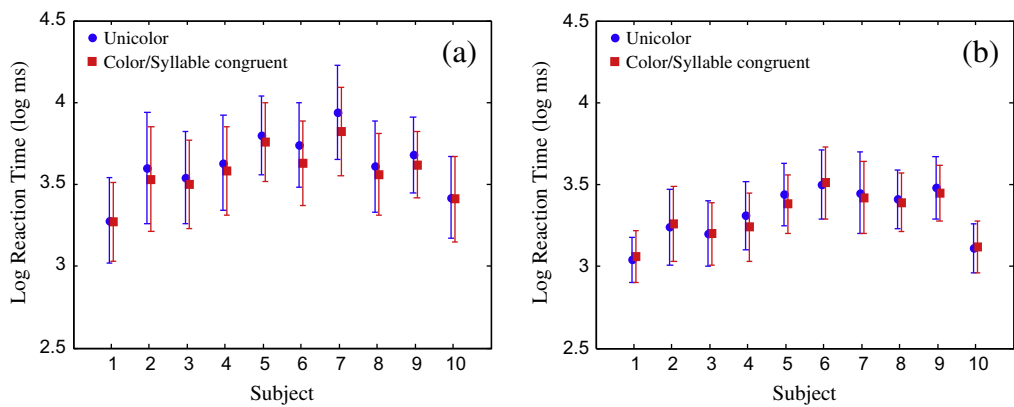


Fig. 3. Average log reaction times (average values \pm standard deviations) for each subject in Experiment 1 for the two color conditions and the two size conditions: (a) the smaller print-size condition and (b) the larger print-size condition.

subjects (Bernard, Scherlen, & Castet, 2007; Kwon, Nandy, & Tjan, 2013; Walsh & Liu, 2014) and the well-known effects of size and frequency on peripheral word recognition and reading speed (Chung, Mansfield, & Legge, 1998; Lee, Legge, & Ortiz, 2003). Our main result is the significant effect of the color/syllable congruent condition on reaction time compared to the unicolor condition: Reaction time was reduced by 9.06% in the color/syllable congruent condition. This decrease in reaction time was significantly higher for smaller character-size trials and marginally significantly higher for trials with low-frequency words. The decrease was 10.38% (and 7.82%) for low (and high) frequency words presented at smaller print size, and 3.91% (and 1.17%) for low (and high) frequency words presented at larger print size.

The average reaction times of Experiment 1 for the different subjects and for the two color conditions and the two size conditions are shown in Fig. 3.

3.2.2. Experiment 2

In Experiment 2, we tested only low frequency words at the smaller character-size (0.5°) with different color conditions. Size and frequency conditions corresponded to the strongest color/syllable congruence effect observed in Experiment 1. Contrary to Experiment 1, Experiment 2 had a *mixed* design with *three* color conditions: the unicolor, the color/syllable congruent and the color/syllable incongruent conditions. Results of the linear mixed-effects model for Experiment 2 are shown in Table 3. As in Experiment 1, there is a significant effect of the rank of trials on reaction time (a decrease of 10.06% in reaction time per 100 trials for the baseline unicolor condition). However, there are no significant differences between the unicolor and color/syllable congruent condition, and between the unicolor and color/syllable incongruent condition. The average reaction times of Experiment 2 for the different subjects and for the three different conditions are shown in Fig. 4.

To summarize our results and compare them to our initial predictions stated in the introduction, we showed that:

- (1) Color/syllable congruence within a word improved word recognition performance, especially for smaller print-size words (Experiment 1) in a *blocked design* (blocked conditions: unicolor and color/syllable congruent conditions).
- (2) This effect was not observed any longer in Experiment 2 in a *mixed design* (mixed conditions: unicolor, color/syllable congruent and color/syllable incongruent conditions).

These results suggest that a strategy based on syllable grouping occurred in Experiment 1, thus improving peripheral word recognition.

4. Discussion

In this study, subjects with a simulated 6° square central scotoma were asked to name single words. Words were displayed at the center of the screen until identification, allowing subjects to make eye movements. In Experiment 1, when two colors were used to segment the different syllables within a word, time to recognize a word was significantly shorter compared to a classical unicolor condition. This result suggested that a syllable decomposition mechanism was at work in the periphery, as it is the case in foveal word recognition (Ans, Carbonnel, & Valdois, 1998; Carreiras, Alvarez, & Devesa, 1993; Conrad, Grainger, & Jacobs, 2007; Ferrand, 2000; Ferrand & New, 2003; Prinzmetal, Treiman, & Rho, 1986; Spoehr & Smith, 1973).

In Experiment 2, we tested whether the effect observed in Experiment 1 relies on a specific syllable decomposition mechanism, rather than on a more general mechanism that improves location encoding (Chung & Legge, 2009) and/or identification of letters. For instance, color boundaries could reduce letter crowding, as observed with mixed polarity letters (Chung & Mansfield, 2009). If this were the case, bicolor syllabic segmentation would also improve word recognition even when color boundaries do not match syllabic boundaries. However, results of Experiment 2

Table 3
Fixed effects results of the linear mixed-effects model in Experiment 2. Results show the effect of the number of trials (#trial) and the effect of the color/syllable congruent condition compared to the unicolor condition (Color) and effect of the color/syllable incongruent condition compared to the unicolor condition (Color). AIC represents the Akaike Information Criteria for the model.

AIC: 5170.59	Estimate	Std. error	DF	t-value	p-value
(Intercept)	8.86	0.19	1969	45.74	<10 ⁻⁵
#trial	−0.0011	0.00047	1969	−2.27	0.02
Color/syllable congruence condition	−0.03	0.04	1969	−0.93	0.35
Color/syllable incongruence condition	0.01	0.04	1969	0.19	0.85

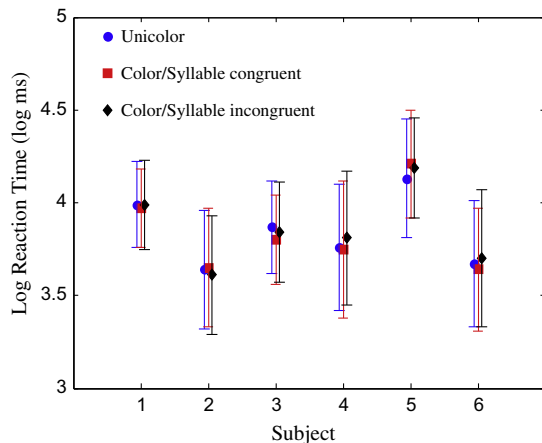


Fig. 4. Average log reaction times for each subject in Experiment 2 (average values \pm standard deviations). During Experiment 2, only smaller print size and low-frequency words were presented.

show no effect of within word segmentation when color boundaries do not match syllabic boundaries compared to the unicolor condition, suggesting that the effect observed in Experiment 1 does rely on the use of syllable information. A second goal of Experiment 2 was to investigate whether the effect observed in Experiment 1 was under stimulus-driven or strategic control (Sperling and Doshier, 1986, chap. 2; Strayer & Kramer, 1994). A stimulus-driven (bottom-up) control has been suggested for the use of syllables as a unit of lexical access during foveal word recognition. For instance, experiments based on illusory conjunction paradigms showed that bottom-up perceptual grouping based on syllables occurs during visual word recognition (Prinzmetal, Hoffman, & Vest, 1991; Prinzmetal, Treiman, & Rho, 1986; Rapp, 1992) and that this effect cannot be explained by orthographic regularities within syllables (Rapp, 1992).

If the same process were underlying the effect observed in Experiment 1, using colors to segment syllables would facilitate the bottom-up syllabic decomposition process, in the same manner it occurs in Carreiras, Vergara, and Barber (2005). Using a mixed design to prevent any strategic component with three different conditions (the color/syllable congruent condition, the color/syllable incongruent condition and the unicolor condition) allowed us to distinguish between these two possibilities. Our results show that the advantage of the color/syllable congruent condition over the unicolor condition disappeared in Experiment 2. This is consistent with the use of a strategy rather than with a stimulus-driven effect to explain the effect observed in Experiment 1. This result exhibits an interesting difference between foveal and peripheral word recognition. It suggests that bottom-up syllabification processes-observed in foveal word recognition do not occur in peripheral word recognition probably because letter visibility in the latter case is degraded. This would be consistent with evidence showing that degrading the visual input (e.g. through foveal progressive demasking) inflates the impact of early perceptual processes (Ferrand et al., 2011). This result must however be slightly qualified because the null result might be due to the smaller statistical power in Experiment 2.

What kind of strategy might be used by readers to improve their peripheral word recognition performance in Experiment 1? One possibility is that readers sequentially focus their attention on each syllable within a word, using colors to localize the different syllables. Engagement of attention on a given syllable would carry on until the identification of this syllable is completed. Subjects would eventually combine the syllables together to identify the word. This strategy may be efficient because syllables in French (as other

languages) have a specific structure with phonological and orthographical regularities. These regularities restrict the size of the syllable lexicon, and may have been used by the subjects to infer identity of certain letters, confused with other letters because of crowding (Bernard & Chung, 2011) or misplaced within the syllable because of positional uncertainty (Chung & Legge, 2009). For instance, in the case of the orthographic syllable “cher” from the word “cacher”, frequent confusions occurring under crowding could bring subjects to perceive a “a” or a “o” instead of a “c” because of their visual similarity. However, this confusion could be corrected by the subjects if they realize that the unicolor letter string made with this letter (“aher” or “oher”) do not constitute an existing syllable.

Experiment 1 also showed that the improvement in performance due to the bicolor syllabic segmentation was largest for smaller letters (size: 0.5°). This condition corresponds to the highest uncertainty concerning letter identity (letter confusion is higher for this condition where the print size is close to the word acuity size) and concerning letter position (if the unit of position is the number of letter slots, Chung & Legge, 2009). Thus, subjects could benefit more from syllable context to correct the larger number of errors concerning letter identities and positions.

In conclusion, we showed that the segmentation of a word in syllables using colors can be useful for readers without central vision to reduce the time needed to recognize a word. This effect has a modest amplitude (the largest amplitude is 10.38% improvement for low frequency and smaller print size words), that represents an interesting theoretical result, but have probably limited practical use for patients with central field loss. However, future research could investigate whether the effect induced by the color/syllable congruent condition can be improved by the addition of other low-level features such as an increase of space or a vertical shift between syllables or other word units such as morphemes (although these units are often aligned with syllable boundaries, they are better indicators of the meaning of the words (Davis, 2004)). In addition, the effect could potentially be increased by a learning procedure in which the color/syllable congruence would be explicitly explained to the subjects.

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